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NAVY EXPERIMENTAL DIVING UNIT
REPORT NO. 5-87

EVALUATION OF AN IMPULSE NOISE PRODUCING UNDERWATER TOOL ON HEARING IN DIVERS

By

LT J. A. STERBA, MC, USNR

JUNE 1987

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DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407-5001

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AUDIOGRAM	UNDERWATER EXPLOSIONS	NEDU TEST PLAN 86-36
AUDIOMETRY	HEARING DAMAGE	UNDERWATER TOOLS
UNDERWATER HEARING	STUD GUNS	HEARING

20. ABSTRACT (continue on reverse side if necessary and identify by block number)

Although it is known that continuous noise underwater may be damaging to human hearing, little research has been done on the influence of impulse noise underwater on hearing in man. NEDU evaluated the effect of an impulse noise producing stud gun, the Ramset 200 HD gun-powder actuated underwater tool, on the hearing in five U.S. Navy divers. Using heavy gun-powder loads and firing 1148 shots underwater into 1/2" thick steel plates, the average peak sound pressure level (SPL) underwater was 185.4 dB ± 0.4 (SEM) (n=668 shots) referenced to 20 uPa. This was equivalent to a SPL of 5.38 PSI or approximately an impulse measurement of 10.76 PSI•msec. The in-air equivalent peak SPL was 150.4 dB, which is 10.4 dB above the current safe exposure limit of 140 dB established by the U.S. Navy. Sound spectral analysis, SPL vs. frequency, was done by one-

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third octave band width analysis to 25.0 kHz and by fast fourier transformation to 62.5 kHz. After firing as many as 40 shots consecutively every 25 sec without the protection of a wet suit hood, no reduction in hearing sensitivity was observed as reflected by an absence of temporary threshold shifts on audiograms taken immediately and two hrs after exposure to underwater impulse noise. Tinnitus was reported in two of five divers after 40 shots, lasting less than one hour. Tympanic membrane erythema, previously thought to be evidence for early acoustic damage from underwater noise, was observed in this study but found to be independent of impulse noise and due only to cold water (58°F, 14.4°C) exposure. Firing greater than 40 shots injured the hand from bruising due to recoil of the Stud Gun. In summary, firing up to 40 shots consecutively in an open-water, unconfined space did not demonstrate any acoustic injury to the diver.

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GLOSSARY

ANSI	American National Standards Institute
c	velocity of sound
dB	decibel
NAVMEDCOMINST	Naval Medical Command Instruction
NAVSEA	Naval Sea Systems Command
NEDU	Navy Experimental Diving Unit
p	density of water
P_m	measured sound pressure
P_{ref}	referenced sound pressure
PMS	Planned Maintenance System
psi	pounds per square inch
PTS	permanent threshold shifts
(re 20 uP_a)	sound pressure has been referenced to 20 uP_a
SCUBA	Self Contained Underwater Breathing Apparatus
SD	Standard Deviation
SEM	Standard Error of the Mean
SPL	Sound Pressure Level
SPL_{air}	Sound Pressure Level measured in air
SPL_{water}	Sound Pressure Level measured in water
Stud Gun	gun powder actuated underwater marine tool
TTS	Temporary Threshold Shift
uP_a	Micro Pascals
Z	impedance of water

ABSTRACT

Although it is known that continuous noise underwater may be damaging to human hearing, little research has been done on the influence of impulse noise underwater on hearing in man. NEDU evaluated the effect of an impulse noise producing stud gun, the Ramset 200 HD gun-powder actuated underwater tool, on the hearing in five U.S. Navy divers. Using heavy gun-powder loads and firing 1148 shots underwater into 1/2" thick steel plates, the average peak sound pressure level (SPL) underwater was 185.4 dB ± 0.4 (SEM) (n=668 shots) referenced to 20 uPa. This was equivalent to a SPL of 5.38 PSI or approximately an impulse measurement of 10.76 PSI•msec. The in-air equivalent peak SPL was 150.4 dB, which is 10.4 dB above the current safe exposure limit of 140 dB established by the U.S. Navy. Sound spectral analysis, SPL vs. frequency, was done by one-third octave band width analysis to 25.0 kHz and by fast fourier transformation to 62.5 kHz. After firing as many as 40 shots consecutively every 25 sec, without the protection of a wet suit hood, no reduction in hearing sensitivity was observed as reflected by an absence of temporary threshold shifts on audiograms taken immediately and two hrs after exposure to underwater impulse noise. Tinnitis was reported in two of five divers after 40 shots, lasting less than one hour. Tympanic membrane erythema, previously thought to be evidence for early acoustic damage from underwater noise, was observed in this study but found to be independent of impulse noise and due only to cold water (58°F, 14.4°C) exposure. Firing greater than 40 shots injured the hand from bruising due to recoil of the Stud Gun. In summary, firing up to 40 shots consecutively in an open-water, unconfined space did not demonstrate any acoustic injury to the diver.

KEY WORDS

IMPULSE NOISE
TEMPORARY THRESHOLD SHIFT
AUDIOGRAM
AUDIOMETRY
UNDERWATER HEARING
SOUND PRESSURE LEVEL
DIVER'S TOOLS
UNDERWATER EXPLOSIONS
HEARING DAMAGE
STUD GUNS
NOISE HAZARDS
NAVSEA TASK #86-21
NEDU TEST PLAN #86-36
UNDERWATER TOOLS
HEARING
UNDERWATER SOUND
TOOLS

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Evaluation of an Impulse Noise Producing Underwater Tool on Hearing in Divers

By:

LT J. A. STERBA, MC, USNR

INTRODUCTION

Exposure to high levels of noise in air is a well known hazard causing permanent hearing loss. However, sufficient knowledge is lacking on the effects of underwater noise on diver's hearing. Divers who have been commonly described as being hard of hearing (Bornmann, 1979) are routinely exposed to a wide variety of high intensity underwater noises (Committee on Underwater Telecommunications, 1970). For example, pneumatic rock drills and chisels, high pressure water jets for hull cleaning, shipboard and portable sonar devices, propeller noise in a harbor, gun powder actuated shark protection (bang sticks), diver recall devices (M-80's) and underwater marine tools (Stud Guns) can all present significant audiological hazards to the diver.

Thus far, underwater audiological research has focused only on the effects of continuous noise on diver's hearing (Reysenbeck de Haan, 1956; Hamilton, 1957; Wainwright, 1958; Hollien, Bekesy, 1960; Montague and Strickland, 1961; Smith, 1969; Smith, et al, 1970; Harris, 1973; Adolfson and Berghage, 1974; Molvaer and Gjestland, 1981) and not intermittent, intense noise known as impulse noise. The purpose of this study (NAVSEA Task #86-21, NEDU Test Plan #86-36) was to systematically evaluate an impulse noise producing, gun powder actuated stud gun (Ramset, Model 200 HD, Rolling Meadows, IL) on divers' hearing as assessed by audiometry.

METHODS

A. Stud Gun Description

This stud gun, which fires a threaded bolt into steel or concrete underwater, is extremely useful for both pier-side maintenance and underwater repair of ships and equipment at sea. The Ramset Underwater Marine Tool, Model 200 HD, Heavy Duty (Fig. 1) fires a .38 caliber blank, propelling a threaded fastener [Model 9140K shank length 5/8", diameter 13/64", and thread length 1 3/16"] (FIG. 2) into a ½" thick mild steel plate measuring 2 feet by 2 feet. The .38 caliber blank is secured at the end of a disposable steel barrel allowing a threaded fastener to be loaded from the opposite opened end at a pre-set distance from the gun-powder charge. By positioning the threaded fastener closer to the gun-powder charge, a more powerful penetration can be made. The barrels used in this study were the most commonly used heavy duty, red loads (Model 738-11) containing 11.8 grains of gun-powder. These industrially loaded .38 caliber blanks are approximately 10% more powerful

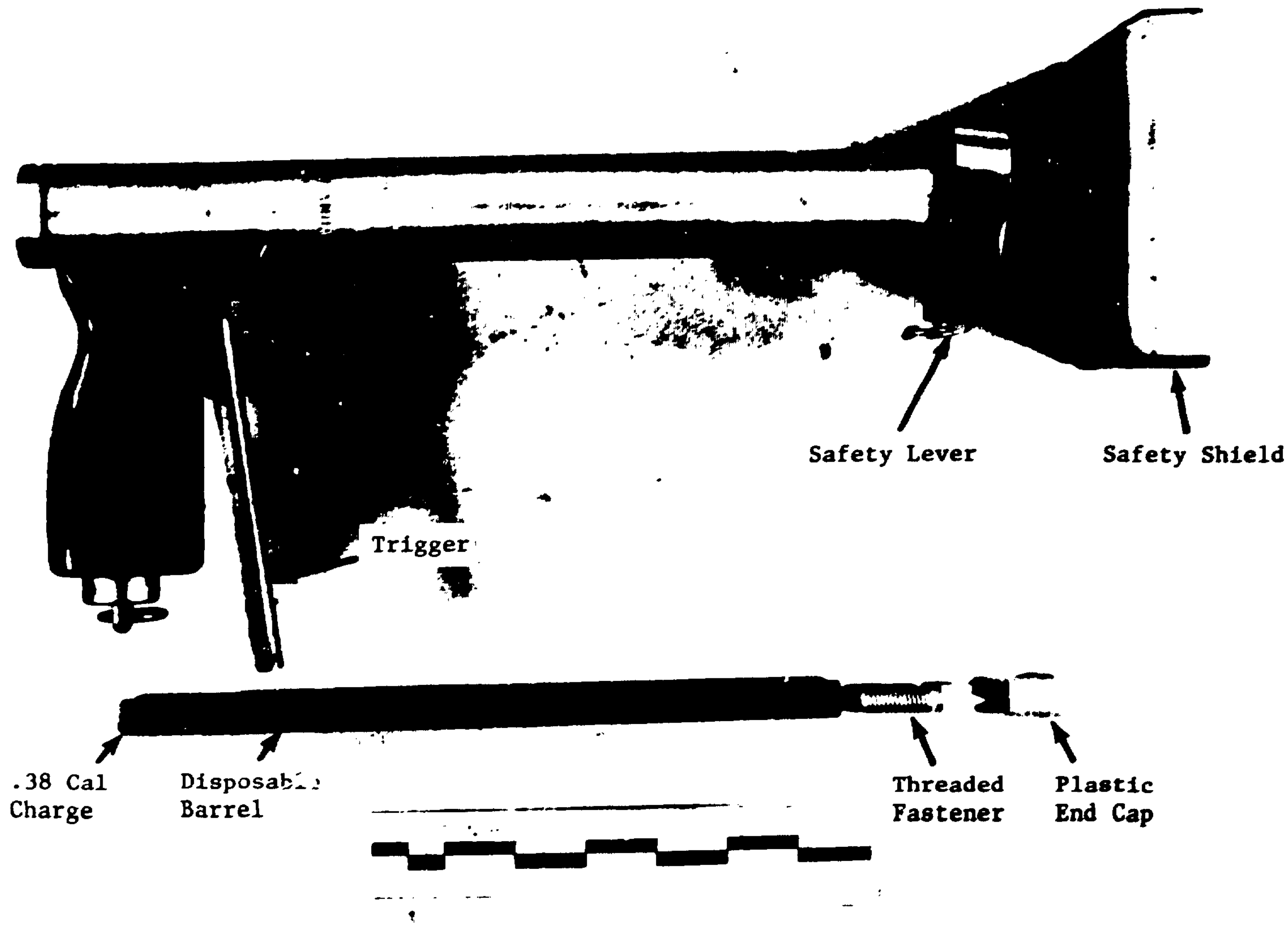


FIG. 1. Ramset Model 200HD Stud Gun (Above) with Disposable Barrel, Threaded Fastener (Model 9140-K) and Waterproofing End-Cap (Below).

than a .44 magnum caliber hand gun round, firing the threaded stud over 1500 ft/sec ± 5% according to the manufacturer. After positioning the fastener down the barrel, a plastic cap is placed over the barrel which is designed to keep water out to a depth of 91.44 MSW (300 FSW).

The stud gun was equipped with two safeties; the first by squeezing the safety lever at the end of the barrel and the second by compressing the extended barrel tip against the steel plate. Both these actions positioned the barrel's .38 caliber primer against the firing pin mechanism. The stud gun could not be fired any other way. The square steel shield at the end of the gun permitted only perpendicular firing, preventing any fishhooking of the studs to shoot back at the operator and also preventing studs from being fired too close to each other.

The shoulder of the threaded fastener is defined as the change in diameter from the threaded portion to the long penetrating point. This is where optimal penetration should stop (FIG. 2, point A). The soft plastic collar on the point served to hold the fastener in the barrel after power positioning with a ramrod.

B. Firing Stage and Acoustic Test Pool

A standard U.S. Navy aluminum diving stage was rigged with two ½" thick mild steel plates on either side, easily removed with vice grips (Fig. 3). The stage was lowered to one foot off the bottom of the 6.1 MSW (20 FSW) deep fresh water acoustic test pool. A nylon web electrically and acoustically isolated the stage from the electrical winch, which was properly grounded to avoid any shock hazard to the diver. The acoustic test pool was a filtered and chlorinated body of fresh water with a temperature of 58°F (14.4°C) isolated in the middle of a large pond by a plastic pool liner, reducing reflected noise. The gantry and walkways were structurally outside the acoustic pool, further reducing noise artifact.

C. Hydrophones and Data Analysis

Two wide band tourmaline hydrophones were used; one placed near the steel plate to trigger the recording oscilloscope (FIG. 3, point A) and the second hydrophone to record the sound at the diver's head, adjacent to his ear (FIG. 3, point B). The recording hydrophone registered the sound of the shot fired on both an oscilloscope for immediate measurement of peak sound pressure level (SPL) and also directly to a high speed magnetic tape (HONEYWELL, Model 101 Tape Recorder, Reproducer, Denver, CO) at 60 inches per second. The high speed magnetic tape was later analyzed shot by shot using a digital frequency analyzer (Bruel and Kjaer, Type 2131, Marlborough, MA) from 32 Hz to 16,000 Hz using a 1/3 octave band width analysis. In addition, a storage oscilloscope (Nicolet Model 4094, Madison, WI) recorded each shot on a floppy disk for fast fourier transformation analysis of the acoustic spectrum of each shot based on every other hertz up to 62.5 kHz. The purpose of such rigorous frequency analysis was to determine any high SPL frequency peaks to anticipate any effects on hearing sensitivity as determined by audiometric testing.

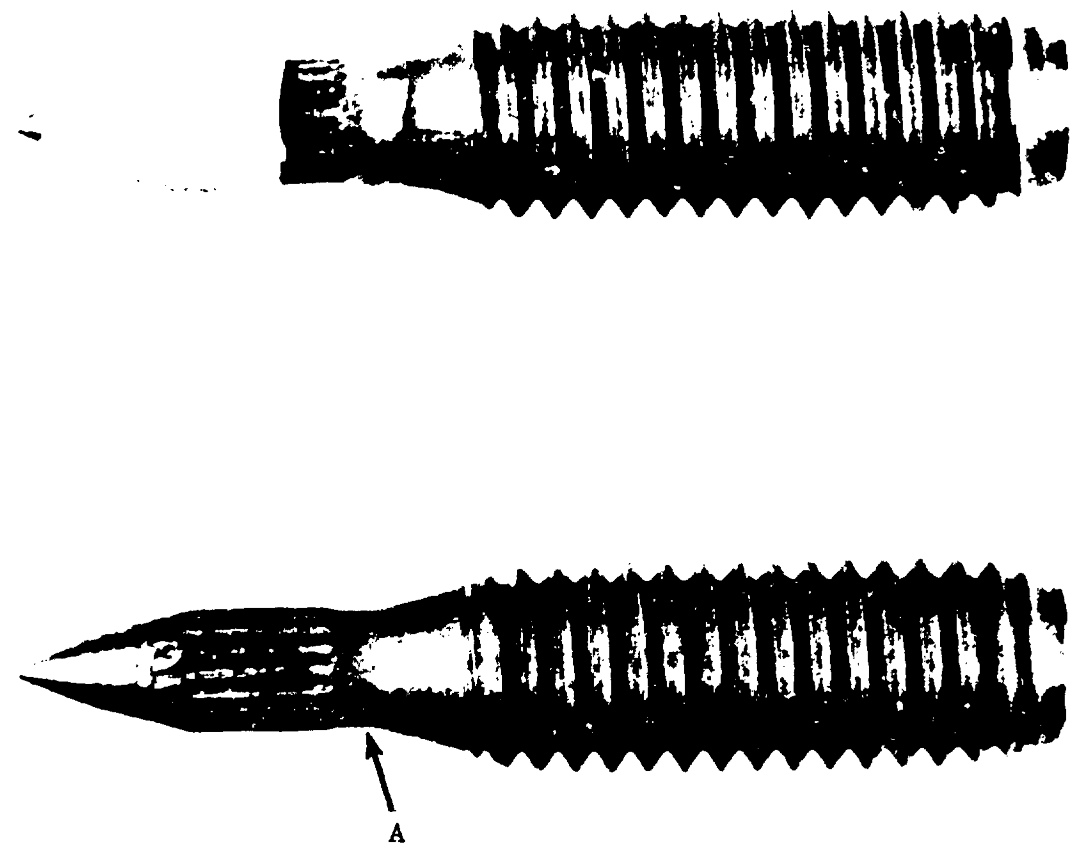


FIG. 2. Threaded Fastener, Model 9140-K, Close-Up. Soft Plastic Colar, Above. Point A Represents Shoulder of Fastener.

FIG. 3. Diver Firing Stud Gun on Diver Stage. A: Trigger Hydrophone, B: Recording Hydrophone.

D. Diver-Subjects

Five male U.S. Navy divers with a mean age of 31.2 ± 3.7 years (ranging from 26 to 36) were used as subjects following audiological screening and giving informed consent. All five had recently completed another acoustic study in which each diver demonstrated highly reproducible audiograms and hearing in the normal range of sensitivity. Prior to this study, a fatiguer stimulus test (Ward, 1963) was performed to screen our subjects for the degree of hearing sensitivity to impulse noise. This was done by testing the left ear at 4 kHz which is the frequency where the maximum reduction in hearing sensitivity would be expected from a broadband, impulse noise. The fatiguer test is a 5 min exposure to a 3 kHz stimulus at 100 dB with a comparison of the pre-exposure hearing threshold to any temporary threshold shift (TTS) in the audiogram seen at one half octave higher than 3 kHz, i.e. 4 kHz at both one and five minutes after the 3 kHz stimulus (Ward, 1963).

This research protocol was approved by the Diver-Subject Human Experimentation Committee at the Naval Coastal Systems Center . All diver-subjects, dive supervisor, audio technician and test director received training and certification from the Ramset Company as underwater tool users and instructors prior to commencing underwater firing.

E. Underwater Firing Procedures

Standard U.S. Navy diving procedures were followed with the diver-subject tethered to a surface tender for line-pull signals. A fully dressed standby diver topside (U.S. Navy Diving Manual, 1985) was immediately available in case of emergency. The following emergency procedures were rehearsed: injured diver with mechanical injury, unconscious diver on the surface and underwater, topside abort, diver abort, and stud gun misfire (Sterba, 1986, Test Plan 86-36).

Following the pre-dive audiometric evaluation as outlined in the Methods Section, the diver dressed in a ¼" neoprene wet suit, in one of the three diving configurations: 1, SCUBA wearing standard dive mask and full cold water hood; 2, SCUBA wearing standard dive mask and no hood; and 3, SCUBA wearing the AGA-Divator full face mask (Interspiro, Branford, CT) and no hood. These three configurations were chosen as the least protective acoustically and the most common to be used in ship's husbandry diving and lightweight underwater work.

After descending to the diving stage, the diver would load the stud gun and commence firing every 25 ± 5 seconds. This was coordinated by line-pull signals to the diver and an intercom on the surface which allowed for all recording gear to be simultaneously operating in the acoustic test facility adjacent to the test pool. Following the specified number of shots fired, the diver would surface, remove his gear and be in the audio booth within 3 minutes for his immediate post-dive audiogram.

The diver held the stud gun with a two-handed grip off to one side (Fig. 3) to avoid any kick-back injury to the face or chest. This position was also the least traumatic to the hand with the repeated powerful kick-backs from high numbers of firings.

F. Experimental Design

Sound is measured with sound pressure level (SPL) measured in decibels (dB). SPL is actually a logarithmic ratio of the measured sound pressure (Pm) divided by reference sound pressure (Pref) in equation (1).

$$SPL(dB) = 20 \log (Pm/Pref) \tag{1}$$

In air, Pref is 20 micropascals (20 uPa) sound pressure which is also equivalent to 0.0002 dyne/cm^2 sound pressure. In water, the usual reference is 1 uPa sound pressure. However, with only air impulse noise research and standards to follow due to a lack of research in underwater impulse noise, our underwater SPLs were referenced to 20 uPa (re 20 uPa) based on 20 x log (20/1) = 26 dB, in equation (2).

$$SPL_{water} \text{ (re 1 uPa)} - 26 \text{ dB} = SPL_{water} \text{ (re 20 uPa)} \tag{2}$$

U.S. Navy Instruction [OPNAVINST 5100.23B, 18103a.(4)] defines hazardous noise as sound pressure <u>in air</u> in excess of 140 dB (re 20 uPa). Therefore, in order to convert SPL in water (SPL_{water} re 20 uPa) to sound pressure level in air (SPL_{air} re 20 uPa), one must correct for the density of water (p) and velocity of sound (c) in order to calculate the impedance of water (Z) based on equation (3) and (4).

$$p \bullet c = Z \tag{3}$$

$$SPL_{air} \text{ (re 20 uPa)} = (SPL_{water})^2/Z \tag{4}$$

To correct for the impedance difference in water and air, use equation (5), (Smith, personal communication, 1987).

$$SPL_{water} \text{ (re 20 uPa)} - 35 \text{ dB} = SPL_{air} \text{ (re 20 uPa)} \tag{5}$$

From a previous study (Mittleman, 1976) using the same Ramset stud gun, heavy gun powder loads and acoustic test pool as in our study, Mittleman recorded SPL_{water} at the diver's head as high as 195.3 dB (re 20 uPa) . Using equation (5), this would be equivalent to <u>in-air</u> SPL_{air} of 160.3 dB (re 20 uPa), which is over 20 dB above the hazardous limit of 140 dB set forth by U.S. Navy Instruction [OPNAVINST 5100.23B, 18103 a.(4)].

Since a wet suit hood properly worn, covering the entire forehead, attenuates sound pressure underwater by 5 to 10 dB (Smith et al 1970; Norman et al 1971) the first shots fired used the wet suit hood to give the diver maximum auditory protection. At a special meeting discussing impulse noise with both U.S. Navy and U.S. Army acoustic research specialists (Sterba, 1986, Test Plan 86-36, Appendix G), it was commonly agreed that 10-20 shots fired would be a safe starting point for underwater firing. Therefore, we started firing with 10 shots, increasing by increments of 10, closely observing for any reduction in the sensitivity of hearing as measured by any temporary threshold shift (TTS) on the audiogram. After using the wet suit hood, divers fired the stud gun without any wet suit hood as the worst case scenario, both wearing a standard face mask and the AGA full face mask.

G. Audiometric Evaluation

Audiograms were performed in a portable audiogram booth with a certified audiometric technician using an automated microprocessor audiogram machine (Tracor Corp., Austin, TX). The audiogram booth was sound tested and found to be within specifications for conducting audiograms in accordance with American National Standards Institute (ANSI) standard S3.6-1969 and Naval Medical Command Instruction (NAVMEDCOMINST 6260.5).

All subjects were instructed not to use music headphones, or be around loud machinery or noisy public places during the study. Prior to each dive, the subjects were asked if they had any symptoms of difficulty hearing, tinnitus or any exposure to loud noise. The tympanic membranes were thoroughly visualized with an otoscope before and after every dive inspecting for any erythema which has been observed after submersed impulse noise exposure by Smith (Smith, personal communication, 1987). Due to technical reasons, we could not photograph the tympanic membrane using a fiberoptic laryngscope and 35 mm camera. Carefully drawn sketches documented any changes observed.

Following the post-dive audiogram, the subject was asked if he had any sensations of fullness in the ears, tinnitus, dizziness, pain in the ears or any rotational movement of the eyes following a shot fired. Follow-up audiograms were made at two hours following completion of the dive due to the reported delays in the TTS seen following impulse noise exposure (Henderson, et al, 1987 and personal communications with Henderson and Patterson, 1987). All divers received a 24-hour follow-up audiogram and, in addition, select divers had 6 and 10 hour post-dive audiograms. A full 48 hrs elapsed before a diver was allowed to be exposed to impulse noise again.

The diver's baseline audiogram was determined by averaging 14 audiograms done before commencing any firing of the stud gun. As defined by U.S. Navy Instruction (OPNAVINST 5100.23B [18105(e)]), a significant temporary threshold shift (TTS) is a change of 15 decibels from the person's baseline audiogram. This level of significance was followed for this study.

RESULTS

A. Audiometric Screening and Baseline

In Table 1, the results of the Fatiguer Stimulation Test with TTS demonstrated hearing within the normal sensitivity range in all of our subjects (Ward, 1963). The change in the divers' audiogram at 4 kHz was less than 25 dB at one min and less than 15 dB at five min. In Table 2, the baseline audiograms were both calculated as a mean of 14 audiograms ± 1 standard deviation (SD) and rounded to increments of 5 dB. The small standard deviation for the mean baseline audiograms demonstrated high reproducibility for all our subjects. No diver-subject was allowed to participate in an experiment unless his pre-dive audiogram had returned to within 5 dB of the baseline audiogram. In every experiment, the 24-hour post-dive audiograms and all pre-dive audiograms were within 5 dB of the baseline audiogram.

B. Acoustic Measurements

The peak SPL, calculated from 668 shots fired underwater, was 185.4 dB ± 0.4 S.E.M. (re to 20 uPa). This corresponds to 188.2 dB (re 20 uPa) as reported by Mittleman (1976) for very similar experimental conditions. As a point of reference, our measured peak SPL of 185.4 dB corresponds to 5.38 pounds per square inch (psi) according to equation (6) (Zimmerman and Lavine, 1955).

$$\text{PSI} = \text{Antilog}\left[(\text{SPL re 20 uPa} + 26)/20\right] \times 1.45 \times 10^{-10} \qquad (6)$$

To convert SPL (re 20 uPa) to PSI based on equation (6), refer to FIG. 4. The measurement of impulse noise can either be peak SPL or the area of the positive deflection of the impulse in FIG. 6, taking into account the duration of the impulse in units of PSI•msec. A conservative estimate of the integration of this area would be the peak SPL in PSI (5.38 PSI) multiplied by the typical duration of the impulse (4 msec) divided by 2, equalling 10.76 PSI•msec.

The spectral analysis of 182 shots fired underwater was done by third octave band width analysis and it is shown in FIG. 5 which demonstrates the broad-band spectrum of impulse noise. It is reasonable to assume that acoustic signals received by our hydrophones were contaminated by vibrations or ringing of both the steel plate into which the studs were shot and the aluminum diver's stage which supported the steel plates and the diver. It would have been unrealistic to control these factors being that a multitude of vibrations would be produced in the underwater workplace using this stud gun.

A typical real-time SPL tracing of a shot fired is shown in FIG. 6 for Test No. 9, Shot No. 12.

Fig. 7 shows the overall spectrum from 0 to 62.5 kHz for the same shot. Figures 8A and 8B expand the spectrum of this shot from 0 to 25 kHz and 25 to 62.5 kHz, respectively with high SPL peaks identified by the specific frequency using the cursor function on the Nicolet digital oscilloscope.

TABLE 1

AUDIOGRAM AT 4 kHz (dB)

Subject	Pre-Fatiguer	Post-Fatiguer 1 Min	(change)	5 min	(change)
T.K.	40	64	(24)	54	(14)
M.G.	36	55	(19)	50	(14)
S.P.	30	47	(17)	40	(10)
S.S.	30	46	(16)	40	(10)
J.N.	34	55	(21)	48	(14)
Mean ± S.D.	34.0 ± 4.2	53.4 ± 7.3	(19.4±3.2)	46.4 ± 6.2	(12.4±2.2)

TABLE 1. Results of Fatiguer Stimulation Test. Stimulus was 100 dB at 3 kHz for 5 min in the left ear, n=5 subjects. Pre- and post-fatiguer hearing thresholds were measured at 4 kHz with post-fatiguer hearing threshold measured at 1 and 5 mins. Comparison of pre and post-fatiguer hearing thresholds shown as (change). Mean ± S.D.

TABLE 2

LEFT EAR(Hz)

SUBJECT	500	1K	2K	3K	4K	6K	8K
TK	6.7(5) ± 2.4	10.0(10) ± 0	17.1(15) ± 2.5	15.7(15) ± 2.6	22.1(20) ± 2.5	27.1(25) ± 3.2	19.6(20) ± 2.3
MG	10.7(10) ± 2.6	18.9(20) ± 2.1	10.0(15) ± 0	14.6(20) ± 3.0	18.5(20) ± 3.0	23.5(25) ± 6.0	23.5(25) ± 4.9
SP	3.2(5) ± 3.1	-2.8(-5) ± 2.5	0.3(0) ± 1.3	1.4(0) ± 2.2	5.0(5) ± 1.9	9.6(10) ± 3.6	5.7(5) ± 4.3
SS	9.6(10) ± 4.1	6.7(5) ± 6.7	-0.3(0) ± 3.6	12.5(15) ± 3.7	11.4(10) ± 4.1	20.7(20) ± 3.3	15.7(15) ± 3.3
JN	12.5(15) ± 3.2	13.2(15) ± 2.4	9.6(10) ± 1.3	6.1(5) ± 2.0	11.4(10) ± 2.3	31.8(30) ± 4.6	24.3(25) ± 4.7

RIGHT EAR(Hz)

SUBJECT	500	1K	2K	3K	4K	6K	8K
TK	3.9(5) ± 3.0	5.0(5) ± 0	21.0(20) ± 2.8	10.7(10) ± 1.3	19.6(20) ± 1.3	22.1(20) ± 4.6	12.8(15) ± 4.7
MG	13.9(15) ± 2.8	18.2(20) ± 3.1	7.5(10) ± 3.2	6.7(5) ± 2.4	18.9(20) ± 2.1	16.7(15) ± 6.9	25.0(25) ± 5.5
SP	2.8(5) ± 5.4	10.7(10) ± 5.4	5.3(5) ± 4.5	8.9(10) ± 5.2	2.1(0) ± 3.1	21.7(20) ± 5.7	10(10) ± 8.3
SS	6.7(5) ± 2.4	4.6(5) ± 3.6	-2.1(0) ± 2.5	1.4(0) ± 2.3	-0.3(0) ± 2.3	9.6(10) ± 3.0	8.9(10) ± 2.8
JN	12.1(10) ± 2.5	12.1(10) ± 1.3	9.6(10) ± 1.3	4.6(5) ± 1.3	8.9(10) ± 2.1	18.5(20) ± 1.3	20(20) ± 3.3

TABLE 2. Baseline audiograms for Left and Right ears for each of five experimental subjects; mean ± SD and rounded value (dB) rounded to increments of 5 dB in parentheses, n=14 audiograms.

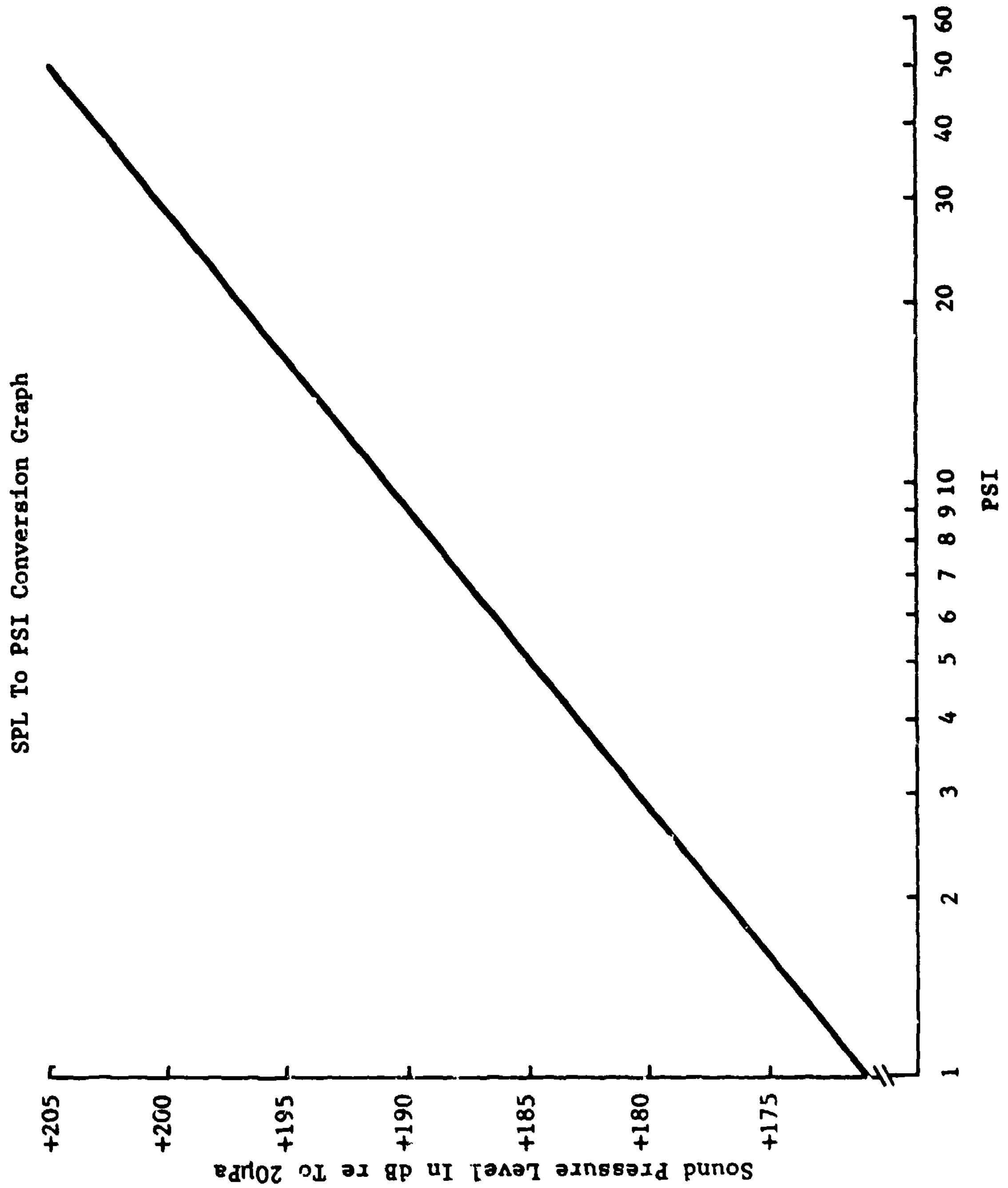


FIG. 4 SPL (re 20 uPa) to PSI Conversion Graph.

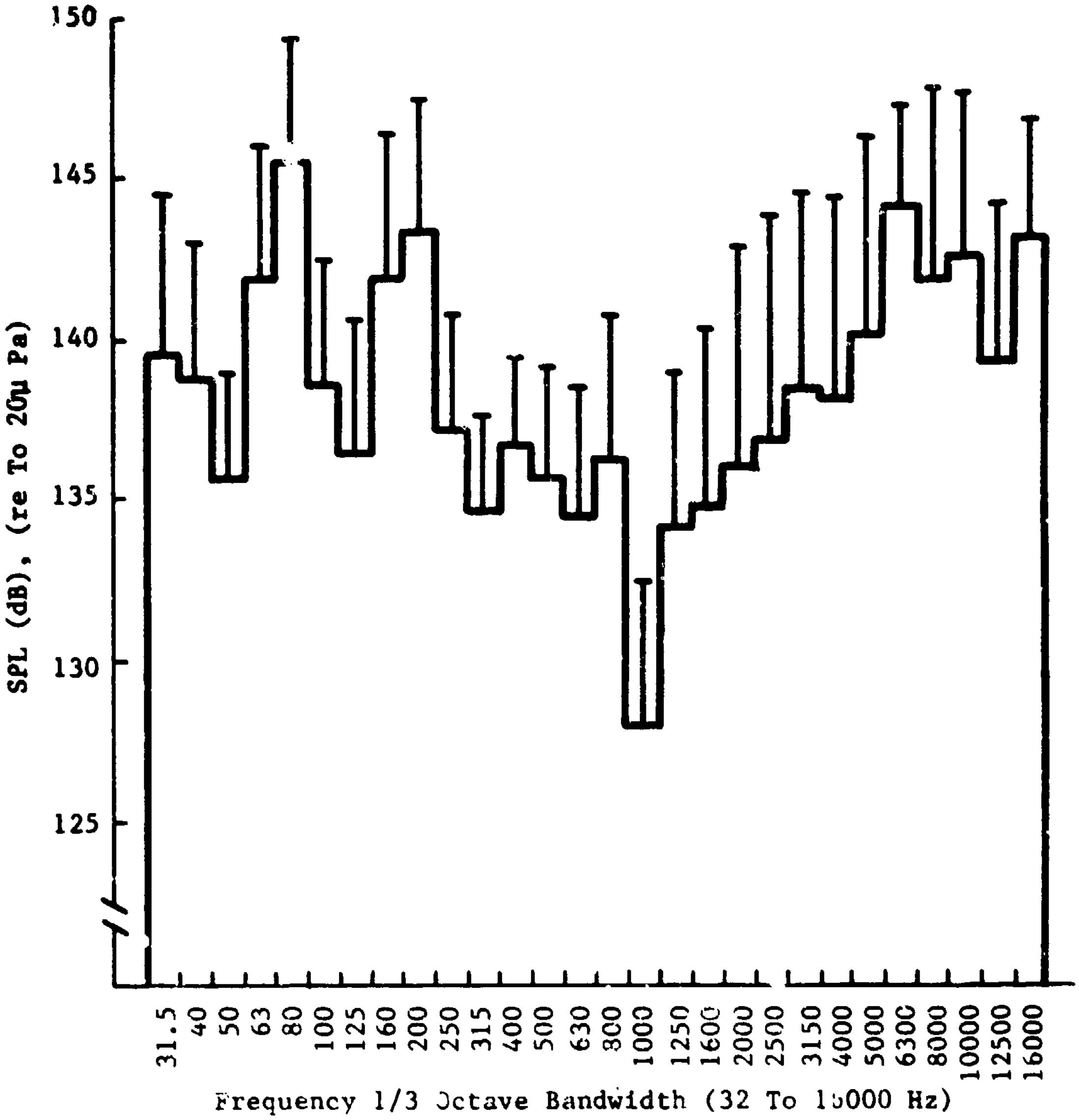


FIG. 5 **Sound Frequency Spectral Analysis, Based on Third Octave Band Width From 32 to 16,000 Hz, n=182 impulses.**

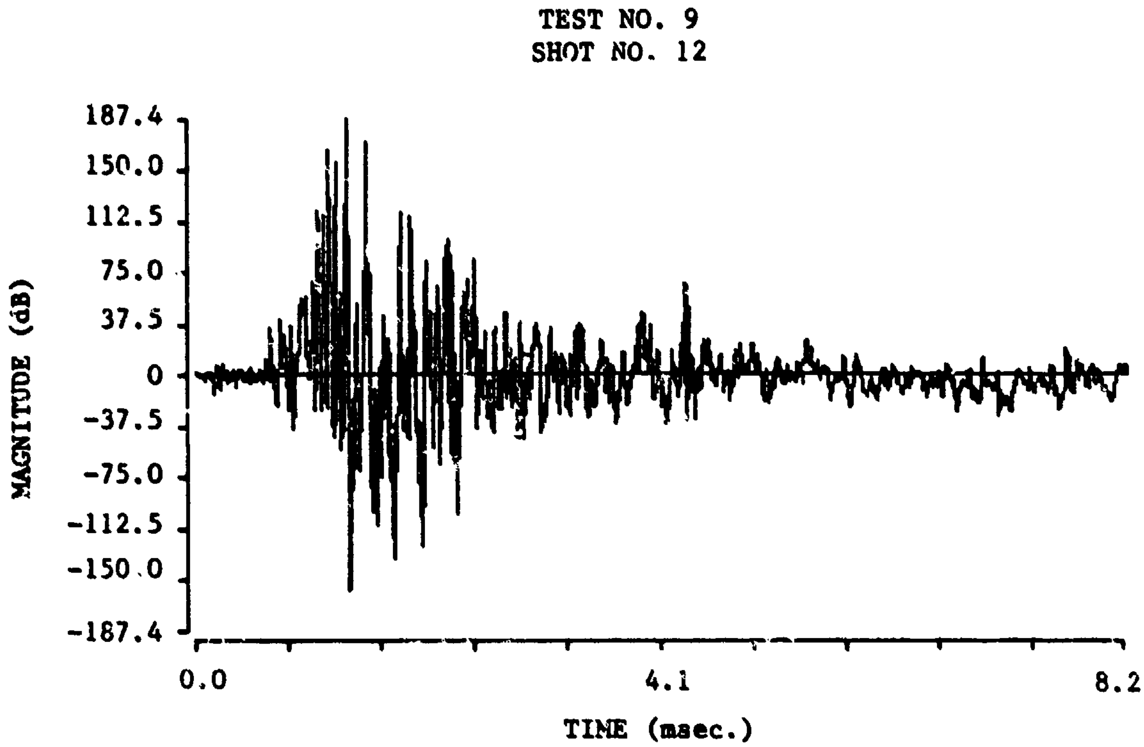


FIG. 6. SPL vs. Real Time (Time Domain Data) of Test No. 9, Shot No. 12.

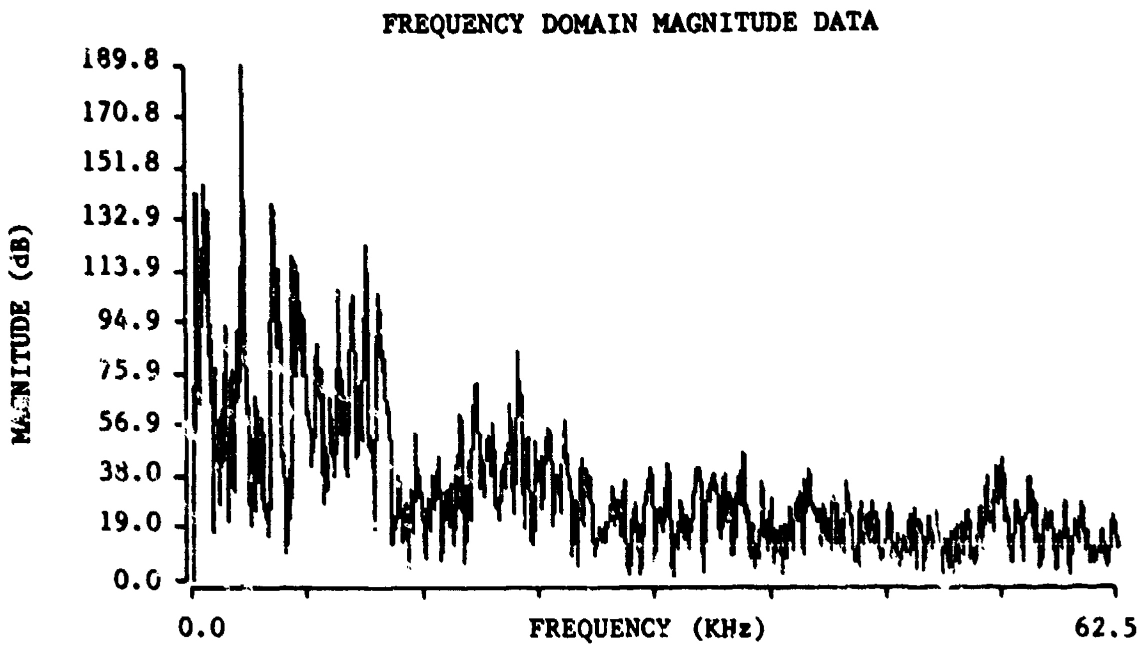
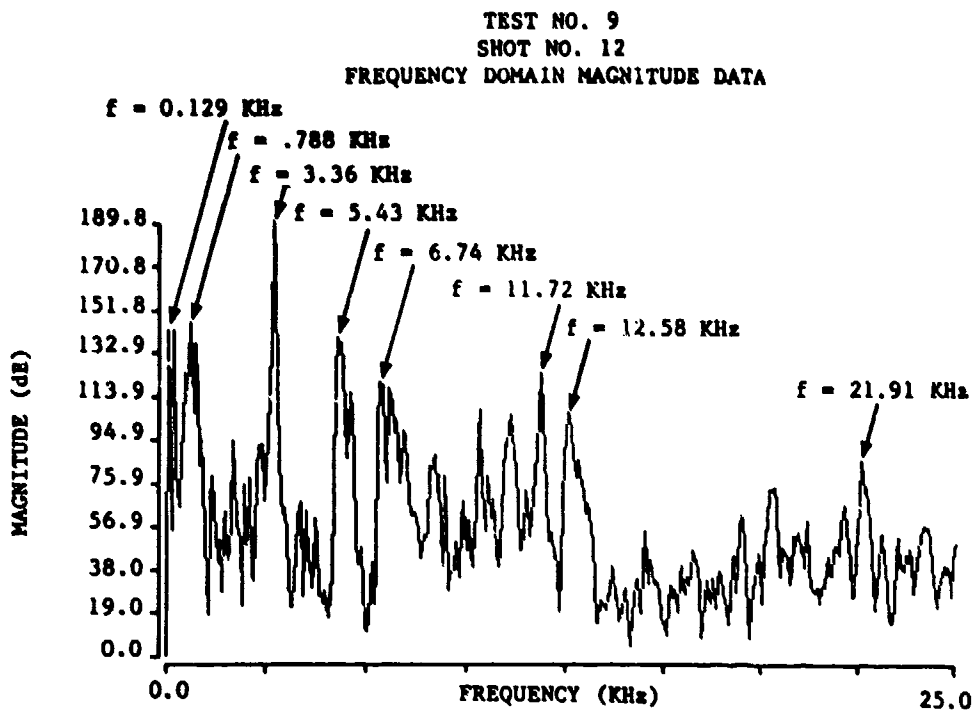
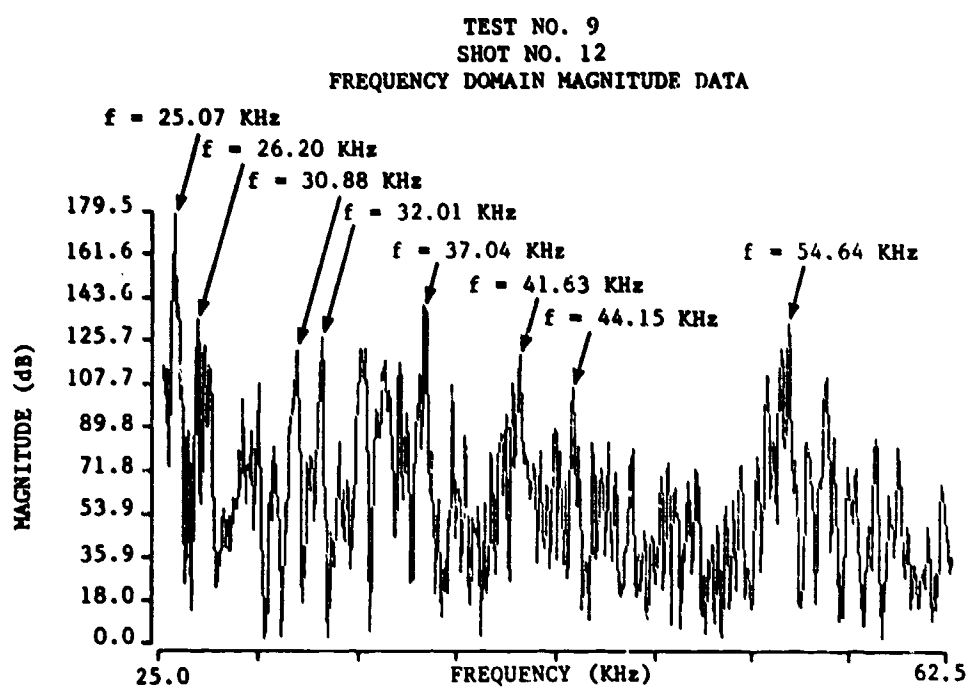


FIG. 7. SPL vs. Freqency (Frequency Domain Magnitude Data), 0 to 62.5 kH, by Fast Fourier Transformation. Experiment No. 9, Shot No. 12.





FIGS. 8A and 8B. SPL vs. Frequency. 8A, Above: 0 to 25 kHz; 8B, Above: 25 to 62.5 kHz, Test No. 9, Shot No. 12.

Having reviewed the 49 shots analyzed by fast fourier transformation, the majority of the high magnitude SPLs occurred in the first 3 to 4 milliseconds, with a decline in the SPL from about 120 Hz to approximately 35 kHz. There were no commonly observed SPL peaks other than around 122-129 Hz.

Again, frequency analysis was done to help predict at which frequencies the SPL peaks occurred to anticipate TTS relative to the frequencies tested on the audiogram.

C. Audiometry, Tympanic Membrane Erythema and Head Injury

No significant TTS was ever observed either immediately or two hours after consecutively firing as many as 80 shots while wearing the wet suit hood. There were no complaints of tinnitis, dizziness, fullness or pain in the ears or any sensations of rotational movement of the eyes. There was no erythema of the tympanic membrane observed in any of the divers wearing the wet suit hood. All divers felt a small pressure wave as the shot fired, but did not describe the shot as loud or uncomfortable. Even though wet suit gloves (1/4" neoprene) were worn, there were complaints of mild to moderate bruising of the muscle group at the base of the thumb (thenar eminence). This occured in excess of 40 shots consecutively fired wearing the hood at the onset of the experiment. This bruising lasted nearly 5-7 days for all divers firing 50-80 shots wearing the hood. Consequently, no shots greater than 40 were subsequently fired in the next phase of the experiment with the diver not wearing a hood. These divers also noticed a change in their penmanship for a few days after such a high number of firings. No residual effects such as reduced grip strength, poor penmanship or pain were noted when firings were limited to 40 shots fired consecutively.

After firing up to 80 shots wearing the hood, the hood was removed and we began firing 20 shots increasing by increments of 10 up to 40 shots. Without the hood, a standard SCUBA mask and AGA full face mask were worn. Although two out of the five divers complained of ringing of the ears following exposure to 40 shots, this lasted for only 30 minutes and was not accompanied by any significant TTS. Each of the five divers fired 40 shots at least twice on separate days and never experienced a TTS immediately or two hours after firing the stud gun.

After firing without the wet suit hood, most divers described hearing a loud, metallic component to the shot fired into the steel plate. This, however, was not uncomfortably loud. There were no complaints of dizziness, fullness or pain in the ears or any rotational sensation in the eyes. Erythema of the tympanic membrane, especially the vascular strip along the malleus and in the pars flacida region of the superior portion of the tympanic membrane was seen in all divers not wearing the wet suit hood. Control experiments were designed allowing the diver to stay submerged for the same duration as 40 shots (15-20 minutes), but in the absence of any impulse noise. The same degree and location of erythema was again observed in all divers. This observed erythema from immersion in cold water (14.4°C, 58°F) both with and without impulse noise exposure lasted 1-2 hours.

On three occasions, very powerful kick-backs resulted in two mild sprains of the thumb metacarpophalangeal joint from hyperextension, and one hyperextension of the wrist. These mild injuries had no sequelae and required 7-10 days to completely resolve.

D. Stun Gun Reliability Testing, Ease of Operation and Safety

Out of 1148 underwater shots fired, 4 split barrels and 4 broken studs remaining in the barrel occurred (FIG. 9).

The total number of misfires that would not refire was 26. Although these barrels had a deep indentation in the primer of the .38 caliber round, they would not fire upon retesting. There were numerous misfires that were successfully refired and were due to a mechanical problem with the stud gun. These misfires were due to the breech plug (FIG. 10, Part #738-218) backing off by unscrewing thus preventing full contact of the firing pin against the primer. This was temporarily corrected by wrapping aluminum foil around the threads, securing the breech plug in its full screwed in position. The searblock (FIG. 10, Part #738-226) was galled and thought to be a source of internal friction against the firing pin, shown in FIG. 10.

The safety lever (FIG. 1) was found to be awkward to use, requiring a twisting of the gun after depressing the lever in order to disengage the safety and compress the spring. Using the gun horizontally underwater without the benefit of gravity, as with dry land vertical firing, was much more difficult. If the safety did not disengage easily, the diver would end up pushing himself away from the metal plate he was firing into before the stud gun could be fired.

DISCUSSION

Having fired 1148 shots underwater and recorded the peak SPL from 668 shots, the Ramset Model 200HD Stud Gun produced a very consistent SPL_{water} averaging 185.4 dB, corresponding to a SPL_{air} of 150.4 dB. This in-air equivalent value of 150.4 dB is over 10 dB above the 140 dB hazardous limit for impulse noise set forth by Navy Instruction [OPNAVINST 5100.23B, 18103a.(4)]. However, all five diver-subjects never demonstrated a significant TTS either immediately following exposure or two hours later. The reason for the recently observed one to two hour delay in the temporary threshold shift following impulse noise exposure in man is not known (Patterson, personal communication, 1987) and may be due to metabolic disturbances in the inner ear hearing organ known as the cochlea.

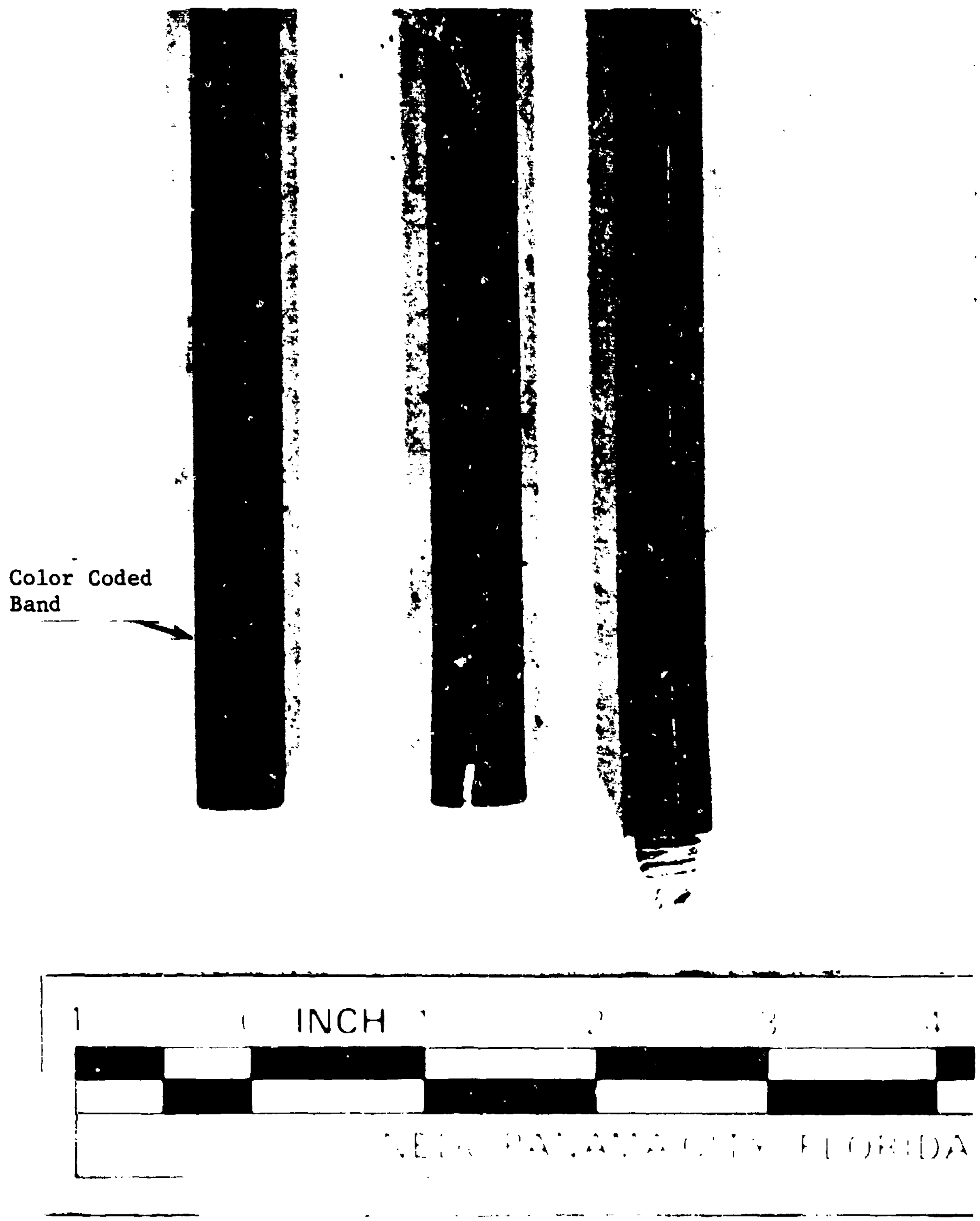


FIG. 9. TOP: Broken Stud, Sheared Off at Shoulder. MIDDLE: Split Barrel, Running Entire Length of Barrel. BOTTOM: Normal Barrel for Comparison.

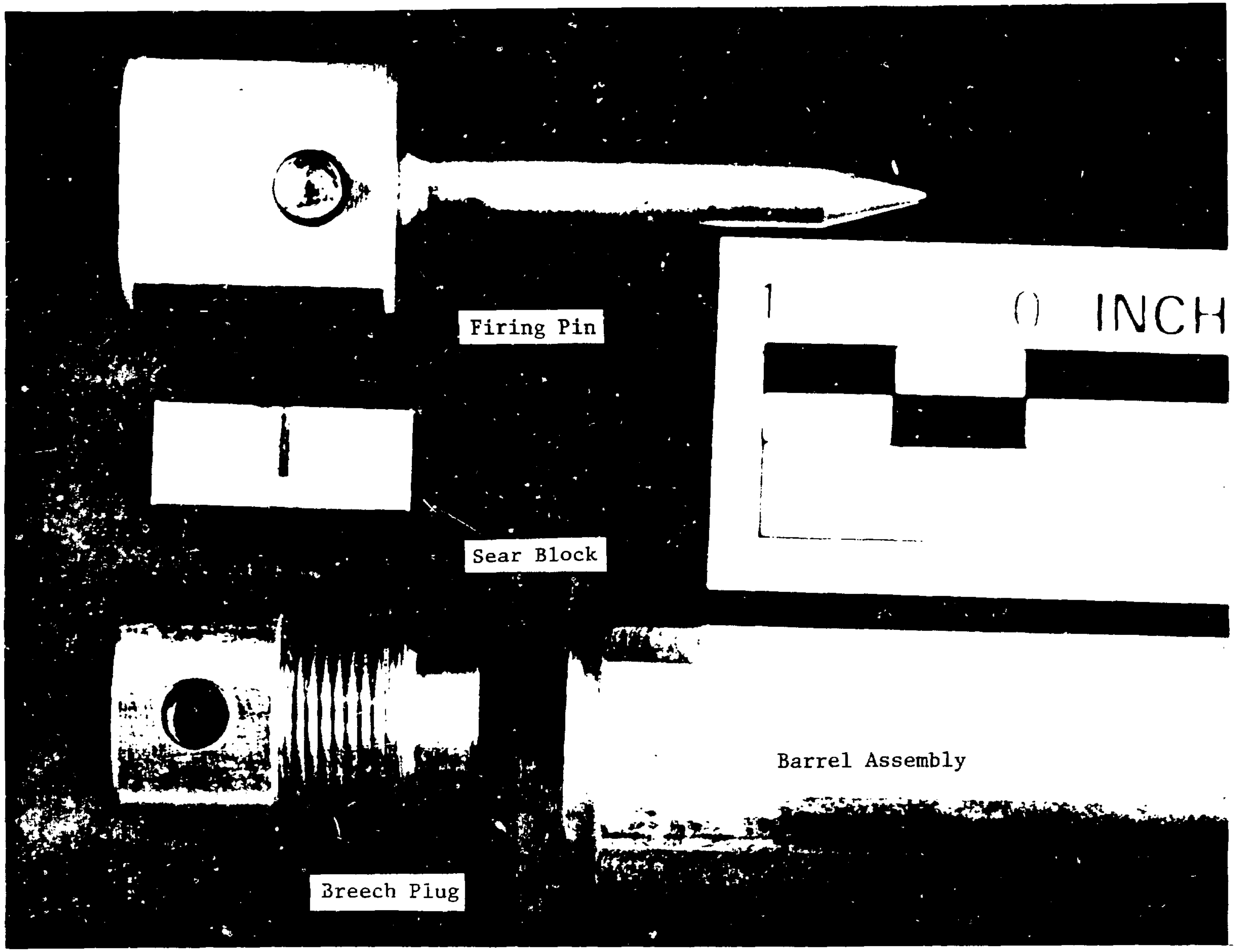


FIG. 10. Firing Pin, Sear Block, Breech Plug and Assembly.

FIG. 11. Recommended Two-Hand Grip, Held to the Side Preventing Recoil Injury to the Head or Chest.

Due to significant trauma to the hand from the powerful recoil of the stud gun, we could not test above 40 consecutive shots with no wet suit hood protection. However, it was observed in two out of five diver-subjects that 40 shots without the hood produced high frequency tinnitis lasting less than one hour, again with no TTS demonstrated. It is possible that by shooting above 40 shots without a wet suit hood, or using the stud gun in a confined space increasing both reflected noise and impulse noise duration, one may induce a temporary threshold shift with this stud gun. From this study in an open-water unconfined environment, rapid firing up to 40 shots consecutively, almost as fast as possible, did not cause acoustic injury to the diver.

Reliable operation by reducing misfires would occur with a nylock on the breech plug to prevent unscrewing and avoiding over-lubrication of the firing mechanism. A harder grade of steel for the searblock will also decrease internal friction. To improve safety, (1) the hand grip should be smaller avoiding injury to the thumb; (2) a safety should be designed near the trigger for ease of operation and safer two-handed operation; and (3) the barrel should be knurled and safety stamped for firing to the side, away from face or chest.

Presently, Ramset is investigating how many times these barrels can be safely reloaded with new .38 caliber blanks in order to save money. These barrels would need a better rust-proofing coating since they will rust easily even in fresh water for 24 hours. Also, a wider color coded band of paint corresponding to the power of the load has been proposed to better mark these barrels near the open end of the barrel (FIG. 9, Lower Barrel).

An unloaded barrel has the waterproof plastic end-cap covering the .38 cal end of the barrel. After positioning the threaded fastener down the barrel, the diver pulls off the end-cap usually by biting it in his teeth and then pushes it on the opened end of the barrel, waterproofing it. This, however, puts small bite holes in the cap and can prevent good waterproofing of the barrel. A warning to this effect will be be brought out in both the owner's manual and training aids.

Concerning safe distances from an underwater impulse noise, most of the animal research on underwater blast injury has been done at the Lovelace Foundation for Medical Education and Research using the sheep model. This model best represents both the intestines and lungs in man (Richmond, et al, 1973). Low level explosions caused intestinal contusions and hemorrhage with high level explosions causing petechial hemorrhaging in the sheeps' lungs. In the Lovelace tests, no test animals received any intestinal or pulmonary injuries at impulse levels below 6 PSI•msec with peak SPL, in excess of several hundred psi. Based on this animal research, criteria for the safety of an unprotected swimmer exposed to an underwater blast has been set at a impulse level of 2 PSI•msec with a peak SPL of 100 psi (Gaspin, 1983). However, in British manned studies (Christian and Gaspin, 1974, Appendix A) unprotected divers were exposed to much higher impulse levels of 35-45 psi•msec with peak SPLs of 120-150 psi. No discomfort to their ears or torso was reported and only a sensation of a bang on the head without any sequelae was observed.

In our studies, the shock impulse level was moderately high at 10.76 PSI•msec, but with an overall low value of the peak SPL of 5.38 PSI and no complaints of discomfort to the ears, chest or abdomen. The divers all felt a mild shock wave in their face but this was not at all uncomfortable.

The Lovelace Foundation determined that the natural oscillation frequency of the lungs of sheep, which may closely represent human lungs, is about 50 Hz (Fletcher et al, 1976). As seen in all shots analyzed by FFT in our study the lowest frequency with a high SPL amplitude was 122-129 Hz. Therefore, the lungs would most likely not be affected by this stud gun.

Concerning the effect of impulse noise on other tissues, there is a theoretical risk of inducing decompression sickness in a diver exposed to the sound pressure wave of underwater impulse noise. The rapid change in tissue pressure caused by impulse noise may precipitate nitrogen bubble formation in a nearby diver either decompressing or ascending from a dive approaching the no-decompression limit.

Smith noted erythema of the tympanic membrane in divers not wearing a wet suit hood following underwater exposure to impulse noise (Smith, personal communication, 1987). The water temperature in his study was 60°F (15.5°C), very close to our study, 58°F (14.4°C). Since the degree and duration of erythema was the same whether or not the diver-subject was exposed to impulse noise in our study, we feel this erythema was cold water induced and is not a reliable sign of acoustic trauma to the tympanic membrane.

Montague and Strickland (1961) and Smith (1970) reported their divers describing a visual effect of rotational movement of the eyes upon exposure to intense underwater noise. This is known as an oculo-gyral effect or Tullio phenomenon . Our divers did not report any visual disturbances using this stud gun. This may be due to the short duration of the impulse noise compared to continuous underwater noise used by Montague and Strickland (1961) and Smith (1970).

Since the dynamic sensitivity of the human ear is greater underwater than in air for frequencies below 125 Hz and above 16 kHz [as explained in an excellent review by Smith (29)], the in-air permissible exposure limits for human hearing may not apply underwater. Before a reliable hearing conservation program for underwater impulse noise can be established, further research is needed including empirically testing impulse noise producing devices. In addition, the basic mechanism for hearing underwater needs to be defined taking into account both bone and tympanic pathways of hearing.

CONCLUSION

The Ramset Stud Gun, Model 200 HD, produces a peak SPL over 10 dB above the safe exposure limit established for impulse noise by the U.S. Navy. Despite rapid firing up to 40 shots without the protection of a wet suit hood, there was no observed reduction in the sensitivity of hearing in five diver-subjects. This was demonstrated by an absence of temporary threshold shifts in the post exposure audiograms. Firing greater than 40 shots in rapid succession produced significant bruising of the hand due to stud gun recoil.

Recommendations to improve both reliability and safety include: (1) using a nylock on the breech plug, (2) a harder grade of searblock steel, (3) a safety designed near the trigger, (4) the stud gun external barrel being knurled and safety stamped and (5) the owner's manual and training aids to be updated.

Further basic research is needed to determine the effects of underwater impulse noise on hearing in man before safe exposure limits can be established.

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